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14. ABSTRACT The objective of the research is to address a number of outstanding issues related to very stable atmospheric boundary layers, including criteria for the collapse of the turbulence, the intermittent behavior and the strong anisotropy of turbulence, horizontal dispersion and meandering of plumes, and the local scaling of the velocities in terms of predictable or measurable parameters.					
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## Report Title

### Direct Numerical Simulations of Very Stable Atmospheric Boundary Layers

#### ABSTRACT

The objective of the research is to address a number of outstanding issues related to very stable atmospheric boundary layers, including criteria for the collapse of the turbulence, the intermittent behavior and the strong anisotropy of turbulence, horizontal dispersion and meandering of plumes, and the local scaling of the velocities in terms of predictable or measurable parameters.

The approach to the research is direct numerical simulation of stably stratified Ekman boundary layers. Very high resolution, three-dimensional, time-dependent simulations are carried out on computational grids of the order of 1,000 grid points in each spatial direction, using highly accurate spectral and compact numerical methods.

The results of these simulations permit a complete statistical description of velocities, Reynolds stresses, and other terms in the energy budgets. The effect of stratification on the length-scales of the flow is investigated using horizontal spectra of various important dynamical quantities. The detailed information from the DNS allows the use of conditional sampling to compute the statistical properties of turbulent patches, as well as to identify their sources (internal waves, low-level jets, etc.). Finally, the simulation results will also be useful as a guide to field measurements, and to perform a priori tests of turbulence models.

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**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

#### (a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
2012/10/01 1: 3	Erik Lindborg, James J. Riley. Stratified Turbulence: A Possible Interpretation of Some Geophysical Turbulence Measurements, Journal of the Atmospheric Sciences, (07 2008): 0. doi: 10.1175/2007JAS2455.1
2012/10/01 1: 4	JAMES J. RILEY, ERIK LINDBORG. A condition on the average Richardson number for weak non-linearity of internal gravity waves, Tellus A, (10 2007): 0. doi: 10.1111/j.1600-0870.2007.00266.x
2012/10/01 1: 1	O. Flores, J. J. Riley. Analysis of Turbulence Collapse in the Stably Stratified Surface Layer Using Direct Numerical Simulation, Boundary-Layer Meteorology, (01 2011): 0. doi: 10.1007/s10546-011-9588-2

**TOTAL: 3**

**Number of Papers published in peer-reviewed journals:**

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#### (b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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**TOTAL:**

**Number of Papers published in non peer-reviewed journals:**

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#### (c) Presentations

O Flores and JJ Riley. November, 2009. "DNS of stably stratified open channel flow", Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, Minneapolis.

JJ Riley. March, 2010. "Stratified turbulence". Stanford University, invited presentation.

JJ Riley. March, 2010. "Stratified turbulence". University of Texas, Austin, invited presentation.

O Flores, April, 2010. "DNS of turbulent channel flows with stable stratification". University of California, San Diego, invited presentation.

O Flores, June, 2010. "DNS of turbulent channel flows with stable stratification". Northwest Research Associates, invited presentation.

O Flores, June, 2010. "Analysis of turbulence collapse in stably-stratified surface layers using direct numerical simulation". National Center for Atmospheric Research, invited presentation.

JJ Riley, June, 2010. "On Pathways to Turbulence in Strongly-stratified Flows". National Center for Atmospheric Research, invited presentation.

JJ Riley and O Flores. August, 2010. "Study of very stable atmospheric boundary layers using direct numerical simulation", Geophysical Turbulence Workshop, National Center for Atmospheric Research, Keynote Address.

O Flores. September, 2010. "Analysis of stratification effects on the atmospheric surface layer using DNS", U. Politecnica de Madrid, Spain, invited presentation.

O Flores. September, 2010. "Analysis of stable stratification effects on the atmosphere using DNS", KTH (Royal Technical University), Stockholm, invited lecture.

JJ Riley. November, 2010. "Study of very stable atmospheric bondary layers using direct numerical simulation", Portland State University, invited seminar.

JJ Riley. November, 2012. "Turbulence in Strongly-stratified Fluids", 63rd Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, Long Beach, Plenary Lecture

O Flores, JJ Riley, N Malaya and RD Moser. November, 2010."Stable stratification in turbulent Ekman layers", Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, Long Beach.

O Flores and JJ Riley. August, 2011. "Energy balance in stably stratified wall-bounded turbulence", 7th International Symposium of Stratified Flows, Rome, Italy.

O Flores and JJ Riley, September, 2011. "DNS of a stratified Ekman layer with a capping inversion", 13th European Turbulence Conference, Warsaw, Poland.

Number of Presentations: 15.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

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(d) Manuscripts

<u>Received</u>	<u>Paper</u>
2012/10/01 11: 6	Erik Lindborg, James J. Riley. Recent Progress in Stratified Turbulence, Ten Chapters in Turbulence (01 2010)

TOTAL: 1

Number of Manuscripts:

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Books

<u>Received</u>	<u>Paper</u>
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TOTAL:

Patents Submitted

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Patents Awarded

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Awards

James J. Riley

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Washington State Academy of Science (2012)

Elected Chair (Vice Chair, Chair-Elect), Division of Fluid Dynamics of the American Physical Society

Director's Award, US Geological Service Department of the Interior (2010): for exemplary service to the Nation. Deepwater Horizon Oil Spill Response.

NATO Research & Technology Organization Lecturer, Universidad Politecnica de Madrid, Spain (2009)

Senior Visiting Fellow, Isaac Newton Institute, Cambridge University, Cambridge, UK (2008)

Lecturer, Midwest Universities Lecture Tour (2008)

Visiting Award from Universite Paul Sabatier, Toulouse, France (2007)

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Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

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Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Oscar Flores	1.00
<b>FTE Equivalent:</b>	<b>1.00</b>
<b>Total Number:</b>	<b>1</b>

### Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
James J. Riley	0.08	
<b>FTE Equivalent:</b>	<b>0.08</b>	
<b>Total Number:</b>	<b>1</b>	

### Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ..... 0.00

### Names of Personnel receiving masters degrees

<u>NAME</u>
<b>Total Number:</b>

### Names of personnel receiving PHDs

<u>NAME</u>
<b>Total Number:</b>

### Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

**Inventions (DD882)**

**Scientific Progress**

Our results use the technique of direct numerical simulation to study stable atmospheric boundary layers. In particular we have examined when and how the turbulence in the layer essentially shuts down due to night-time cooling at the ground, as observed in the CASES99 field experiment. Of course turbulence in the atmospheric boundary layer has many causes, including the aforementioned ground-generated turbulence, as well as turbulence due to breaking internal waves, turbulence resulting from the shear in low level jets, turbulence due to topographical features, and other mechanisms.

Direct numerical simulation is a computational technique that has been used increasingly in the study of turbulence flows, and now often in the study of turbulent, stably-stratified flows. In direct numerical simulations, all of the relevant length and time scales of motion are resolved. Because of the limited resolution of computer simulations, however, in this approach only flows with Reynolds numbers well below those in the atmospheric boundary layer can be treated. Therefore, only problems and issues that are not strongly Reynolds-number dependent can be addressed by this approach. Since the 'local' Reynolds number is relatively small in the lower part of the surface sublayer under strong stratification, the collapse of ground-generated turbulence is exceptionally well suited for analysis with this technique.

The results of our simulations using smooth, flat ground suggest that ground-generated turbulence shuts down when the Monin-Oboukov scale reduces to the order of the buffer region in the boundary layer, which region is located very close to the ground. Results from non-stratified boundary layer studies have indicated that, over flat surfaces, the buffer region is the home of a nonlinear cycle that sustains the turbulence. Our results indicate that, once the stratification is able to sufficiently disturb that cycle, ground generation of turbulence is shut down. When these arguments are extended to more general rough surfaces, the suggestion is that the turbulence generation over rough surfaces shuts down when the ratio of the Monin-Oboukov length scale and the roughness sublayer height become of order one. This suggestion is consistent with the results from CASES99, and also suggests criteria to be used in RANS and large-eddy simulations of atmospheric boundary layers. A paper based upon our results has been published in Boundary Layer Meteorology. Also, direct numerical simulation results were supplied to Dr. Keith Wilson, ERDC-CRREL for use in testing his modeling.

### **Technology Transfer**